WP EN2017-2

"Preheat-parallel" configuration for low-temperature geothermally-fed CHP plants

Sarah Van Erdeweghe, Johan Van Bael, Ben Laenen, William D'haeseleer

TME WORKING PAPER - Energy and Environment
Last update: March 2017

An electronic version of the paper may be downloaded from the TME website:
http://www.mech.kuleuven.be/tme/research/

KULeuven Energy Institute
TME Branch

"Preheat-parallel" configuration for low-temperature geothermally-fed CHP plants

Sarah Van Erdeweghe[a,c], Johan Van Bael[b,c], Ben Laenen[b], William D'haeseleer[a,c,*]

[a] *KU Leuven (University of Leuven), Applied Mechanics and Energy Conversion Section, Celestijnenlaan 300 - box 2421, B-3001 Leuven, Belgium*

[b] *Flemish Institute of Technological Research (VITO), Boeretang 200, B-2400 Mol, Belgium*

[c] *EnergyVille, Thor Park, Poort Genk 8310, B-3600 Genk, Belgium*

Abstract

A novel CHP configuration is presented, which is fueled by low-temperature geothermal energy and delivers heat to a district heating (DH) system. This so-called "Preheat-parallel" configuration has a higher net electrical power output ($\dot{W}_{net}$) and a higher exergetic plant efficiency (η_{ex}) than the convenient series and parallel configurations for the connection to a state-of-the-art 75/50 DH system. For the considered cases, $\dot{W}_{net}$ and η_{ex} are 1.3%−6.4% and 0.4%-pts−1.9%-pts higher than for the parallel configuration, respectively. The highest values correspond to the highest heat demand. With respect to the series configuration $\dot{W}_{net}$ and η_{ex} are 2.1%−9.9% and 0.7%-pts−3.0%-pts higher, respectively, where the highest values correspond to the lowest heat demand. Furthermore, the optimal CHP configuration - series, parallel or "Preheat-parallel" - is discussed. The optimal configuration depends on the DH system requirements. Supply and return temperatures in the range of $T_{supply} = 40 - 110°C$ and $T_{return} = 30 - 70°C$ are considered. We conclude that the series and parallel configurations have the best performance for the connection to low-temperature and high-temperature DH systems, respectively. However, for a wide range of T_{supply} & T_{return}, the "Preheat-parallel" configuration is the most appropriate. The *preheating*-effect is the main feature of the "Preheat-parallel" configuration, and is more useful for a large temperature difference $T_{supply} - T_{return}$ and for low values of T_{return}. Furthermore, we found that for high heat demands and small temperature differences $T_{supply} - T_{return}$, the "Preheat-parallel" or series configurations

*Corresponding author
Email address: `william.dhaeseleer@kuleuven.be` (William D'haeseleer)

might perform better than the parallel configuration for the connection to a high-temperature DH system.

Keywords: low-grade geothermal energy, CHP, ORC, district heating, thermal network

1. Introduction

Deep-geothermal energy is able to provide a constant heat flux to the earth surface which can lead to a constant power output of geothermal power plants if this heat is harvested [1]. This is in contrast to the intermittent power output of PV solar panels and wind turbines.

In Central and Western Europe, temperatures of deep-geothermal energy are often below $150°C$. For these low temperatures, binary power plants are the most appropriate [2, 3]. The geothermal water (usually referred to as 'brine') transfers heat to a secondary fluid which undergoes a power generation cycle. Organic Rankine Cycles (ORC) are a state-of-the-art technology for this low-temperature heat-to-power conversion [4] and have widely been studied in the modern literature. In previous work [5], we have provided a literature survey which covers power generation via ORC and ORC working fluid selection. For those topics, the reader is referred to that paper [5][1].

Due to the high drilling costs and the low cycle efficiency, binary geothermal power plants are often not economically feasible. On the one hand, the plant efficiency and economics might be increased by using multiple (renewable) energy sources in a so-called "hybrid" plant. For example, Astolfi et al. [6], Tempesti et al. [7], Zhou et al. [8], Zhou [9] and Cardemil et al. [10] have studied a hybrid power plant using (low-temperature) geothermal energy and thermal solar collectors. They have found that the solar-geothermal hybrid concept could represent a good opportunity for lower cost electricity production from the sun, at the same time increasing the attractiveness of many (low-temperature) geothermal sources.

On the other hand, the plant economics might be increased by the combined heat-and-power (CHP) production from a single low-temperature geothermal source. This topic has also been touched upon in the literature survey of previous work [5] but is discussed here in detail because of its relevance for

[1] The non-referred preprint version is available at `https://www.mech.kuleuven.be/en/tme/research/energy_environment`

this paper. Previous studies on low-temperature geothermally-fed CHP plants have been performed by Li et al. [11], Rubio-Maya et al. [12], Fiaschi et al. [13], Guo et al. [14], Habka et al. [15] and Heberle et al. [4].

Li et al. [11] have compared two CHP configurations based on first and second law analysis. The first configuration is the series connection of an ORC, an oil gathering and transportation heat tracing system (OGTHT) and an oil recovery system (OR). The second configuration is a parallel configuration of the ORC and the OGTHT systems, followed by the OR in series. A geothermal source temperature of $100-150°C$ was considered. They found that R601a has the best performance for both cycles. They also found that the series configurations is preferable for high geothermal water inlet temperatures and low heat source temperature, and just the reverse for the parallel configuration. Moreover, they have shown that there exists a critical mass flow rate for which the net power output of both, the series and the parallel configuration, are equal.

Rubio-Maya et al. [12] have reviewed the cascade utilization of low- and medium-temperature geothermal resources in different regions around the world. They have concluded that the use of geothermal energy in cascade improves the resource utilization.

Fiaschi et al. [13] have investigated a so-called "Cross-Parallel" CHP configuration, which is aimed to deliver high-temperature heat for industrial use. They considered a geothermal source temperature of $170°C$, and heat delivery at temperatures of $80 - 140°C$ and flow rates of $3 - 13$kg/s. They found that the brine injection temperature and the heat exchanger irreversibilities are lower compared to the parallel configuration, and that the net electrical power generation is up to 55% higher for the investigated parameter values of the geothermal source and heat delivery.

Guo et al. [14] have studied a novel CHP configuration, which is the series connection of an ORC, a heat exchanger subsystem and a heat pump. Based on the results of a techno-economic analysis, they have optimized the ORC parameters and defined the optimal working fluid out of 27 considered working fluids. Depending on the optimization criterion, the results were different. E170, R600 and R141b showed the lowest value for the ratio of total heat transfer area to net power output and the lowest electricity production cost, whereas R236ea gave the largest net power output.

Habka et al. [15] have proposed 4 new CHP configurations which deliver heat to a district heating (DH) system. The geothermal source temperature and flow rate were $100°C$ and 1kg/s, respectively.

The supply & return temperatures of the DH system were $T_{supply} = 75°C$ & $T_{return} = 50°C$ and the heat demand was $110 - 170$kW. For the investigated boundary conditions, all CHP configurations have shown higher values of the exergetic plant efficiency, while the stand-alone electrical power plant produces more electricity. Some of the new CHP configuration were able to reach exergetic plant efficiencies over 70% and, in addition, the optimal configuration was able to generate 88% of the pure electrical power plant output.

Heberle et al. [4] have compared the series and parallel CHP configurations based on a second law analysis. They considered geothermal source temperatures up to 450K($= 177°C$) and supply and return temperatures of the heating network of $T_{supply} = 75°C$ & $T_{return} = 50°C$. They found that due to the combined heat-and-power generation, the second law efficiency of a geothermal power plant can significantly be increased. For the investigated plant parameters, the series circuit was the most efficient concept with exergetic efficiencies up to 55.5%.

Besides the study of combined heat-and-power plants, multi-energy generation systems have been studied in the modern literature as well. Among others, Zare [16], Akbari Kordlar et al. [17], Boyaghchi et al. [18] and Akrami et al. [19] have studied multi-energy systems based on low-temperature geothermal energy.

Zare [16] has compared two trigeneration systems based on a second law analysis. The first system is a series configuration of an ORC, an absorption chiller and a water heater for domestic hot water production. The second system is the same as the first system, however, a Kalina cycle has been considered instead of the ORC. The author has found that the second system (with the Kalina cycle) has a better second law performance. For a heat source temperature of $120°C$, the second law efficiency of the second system is 50.36% compared to 46.51% for the first system. The corresponding net power generation of the Kalina cycle is 12.2% higher than for the ORC cycle.

Akbari Kordlar et al. [17] have investigated the performance of a combined cooling an power cogeneration system. The system is a parallel configuration of an ORC and an absorption refrigeration cycle, using a common condenser. A low-temperature geothermal source at a temperature of $133.3°C$ and a mass flow rate of 100kg/s has been considered. They have performed thermodynamic optimizations towards optimal energetic and exergetic efficiency as well as an economic optimization towards minimal total product cost. The authors have concluded that the economic optimization objective is the best as it results in a 20.4% and 24.32% reduction of the total product cost, compared to the optimization towards the energy and the exergy efficiency, respectively. Furthermore, they have found that the sum of capital cost and exergy destruction cost rates are the highest for the turbine, followed by the condenser and the absorber.

Boyaghchi et al. [18] have studied the performance of an integrated system consisting of a cascade ORC, a liquefied natural gas vaporization process and a proton exchange membrane (PEM). Four types of energies are produced: hydrogen production in the PEM, heating load for vaporizing the liquefied natural gas, cooling effect and electrical power. For a geothermal source temperature of 406K and at a flow rate of 19kg/s, the energy and exergy efficiencies are 82.6% and 38.2% respectively, the hydrogen is produced at a rate of 1.468g/s and the total product cost rate of the system is about 1170$/h. Furthermore, the authors have proposed some performance improvement measures based on a parametric study and a multicriteria optimization using the Non-dominated Sort Genetic Algorithm II.

Akrami et al. [19] have presented a multigeneration energy system based on a low-temperature geothermal source with a temperature of $200°C$ and a flow rate of 15 kg/s. The brine subsequently delivers heat to an ORC and to a system for hot tap water production, before it is reinjected. The working fluid of the ORC is Isobutane. After expansion in the ORC turbine, the Isobutane delivers heat to a water/LiBr absorption refrigeration cycle. Additionally, part of the turbine power is used for hydrogen production in a Proton Exchange Membrane Electrolyzer (PEME). The system generates power (via the ORC system), heat (directly from the brine), cold (via the refrigeration cycle) and hydrogen (via the PEME). For the given source conditions, the system energy and exergy efficiencies are 34.98% and 49.17%, respectively. The net electrical power output, heating and cooling load and the rate of hydrogen production are 952.3kW, 1618kW, 1896kW and 0.052g/s, respectively. Moreover, the unit costs for the net electrical power output, heating, cooling and hydrogen production are 0.1046$/kWh, 22.78$/GJ, 4.622$/GJ and 5.967$/kg, respectively.

Additionally, multi-energy generation systems based on solar energy, waste heat and biomass have been studied, among others, by Bellos et al. [20], Wieland et al. [21], Calise et al. [22], Wang et al. [23], Martelli et al. [24] and Capra et al. [25].

Bellos et al. [20] have performed a parametric investigation of a trigeneration system for application in buildings. The system is a modified absorption heat pump where part of the steam in the generator of the heat pump is extracted to produce electricity in a steam turbine. The refrigeration system generates cold an hot thermal power. The fraction of the steam which is sent to the turbine is the control parameter for regulating the electrical and (hot and cold) thermal power outputs. For a 50% steam extraction to the turbine and a 100kW heat input, which might come from renewable energy sources like solar or geothermal, the exergetic efficiency is about 72%. Furthermore, they have found that the optimal generator temperature is $110°C$ according to a condenser temperature of $50°C$, which can easily be delivered by renewable sources.

Wieland et al. [21] have proposed a two-stage ORC with turbine-bleeding and regenerative pre-heating for application in a CHP plant. The turbine-bleeding is used for heat delivery to a district heating system with supply and return temperatures of $80°C$ and $50°C$, respectively. A thermal oil circuit with temperatures of $240°C$ and $340°C$ has been considered, which are typical temperatures for waste heat and biomass applications, respectively. The authors have shown six different CHP concepts which are discussed in the literature. The parallel and condensation CHP concepts are the most flexible and are compared with the novel concept. The parallel concept has the highest electric efficiencies but the available district heat is limited, to be able to work in co-generation mode. The condensation concepts have lower electric efficiencies but higher available heat. The novel proposed concept combines the good aspects of both. Additionally, they have concluded that the proposed concept is extremely useful when a large share of the district heat has to be delivered by the CHP.

Calise et al. [22] have presented a dynamic exergo-economic simulation model for a novel solar-geothermal polygeneration system. Electricity is produced via an ORC which is fueled by geothermal and solar energy. Afterwards, the geothermal source delivers energy to the Thermal Recovery System (TRS). In the TRS, either the heat is used for heat delivery, or the heat is used to drive a water/LiBr refrigeration system to produce cold. Last, the geothermal source delivers heat to a multi effect distillation system that produces desalinated water from seawater. The authors have found that the global exergy efficiency varies between 40% and 50% when the TRS delivers heat, and between 16% and 20% when the TRS delivers cold. Furthermore, the authors have concluded that the electricity price is scarcely competitive, whereas the price of fresh water is moderately competitive.

Wang et al. [23] have presented a multi-objective optimization of a combined cooling, heating and power system driven by solar energy. The CCHP subsystem combines an ORC with an ejector refrigeration cycle to produce electricity and cold. The authors have used the power output and the total heat transfer area as the objectives. The turbine inlet temperature & pressure, the condensation temperature and the pinch temperature difference in the vapor generator are the optimization variables. The optimal power output and total heat transfer area are 6.40kW and $46.16m^2$ for the power only mode, 5.84kW and $58.74m^2$ for the combined cooling and power mode (summer) and 8.89kW and $38.78m^2$ for the combined heat and power mode.

The work of Martelli et al. [24] and Capra et al. [25] comprises a two-part paper on the optimization of a combined heat-and-power plant. In part A, Martelli et al. [24] have proposed a thermo-economic model for the simultaneous optimization of cycle and turbine design parameters of a biomass-fired CHP. In the investigated set-up, the biomass boiler delivers heat to a thermal oil circuit, which subsequently delivers heat to the ORC. The ORC condenser heat feeds the thermal network. The thermal oil delivers heat to the ORC system at a temperature of $300°C$ and the supply temperature of the thermal network is $80°C$. The thermal power output and net electrical power output are 5.3MW and 1MW, respectively. In part B, Capra et al. [25] have developed a novel part-load operation optimization model for CHP ORCs. They have combined it with the design model (full-load) of part A which has resulted in a two-stage optimization algorithm. The final algorithm allows the optimization of the plant design and size, taking into account the load duration curve of the heat demand and the part-load performance of the cycle. They have concluded that in comparison to the full-load design optimization results of part A, the solution optimized for part-load operation has a lower investment cost, better part-load efficiencies an a higher annual profit.

In this paper, we propose a so-called "Preheat-parallel" CHP configuration fueled by a low-temperature geothermal source. According to the authors' knowledge, this CHP configuration has not been studied in the literature yet. Electrical power is produced by an ORC and heat is delivered to a thermal network (for simplicity called district heating (DH) system further on). The performance of the "Preheat-parallel" configuration is compared with the series and parallel CHP configurations for different DH system requirements (temperature levels and heat demand). The geothermal brine has a temperature of $T_{b,in} = 130°C$ and a flow rate of $\dot{m}_b = 194kg/s$ [2]. The series and parallel CHP configurations, coupled to a thermal network have been discussed in Van Erdeweghe et al. [5].

2. Methodology

First, the working principle of the novel "Preheat-parallel" CHP configuration is explained. Then the models and the objectives are presented. Finally, the assumptions and implementation are delineated and discussed.

2.1. "Preheat-parallel" configuration

A schematic outline of the "Preheat-parallel" configuration is given in Figure 1. The "Preheat-parallel" configuration is the combination of a series and a parallel configuration. The brine delivers heat to the ORC and the DH system in parallel. However, the remaining heat of the brine after having passed the ORC (for simplicity called "ORC waste heat") is used to *preheat* the DH fluid (in DH HEx 1) from the return temperature T_{return} to a temperature T_{mid}. Subsequently, more heat is added in the parallel branch (in DH HEx 2) to reach the required supply temperature T_{supply}.

A basic ORC (as presented in Figure 1) as well as a recuperated cycle are considered[3]. For the basic cycle, starting from saturated liquid in state 1, the working fluid is subsequently pressurized by the pump ($1 \rightarrow 2$), evaporated ($2 \rightarrow 3$), expanded in the turbine ($3 \rightarrow 4$) and finally condensed back to state 1 to close the cycle. Electrical power is produced by the generator which is connected to the turbine. For the recuperated cycle, the superheated vapor at the turbine outlet (state 4) is used to preheat the working fluid at state 2, thereby increasing the cycle efficiency.

[2]Those parameter values have been chosen based on the expected brine conditions in Flanders—internal communication with Ben Laenen.

[3]The recuperated cycle is not shown here. The reader is referred to Walraven et al. [26] for a detailed description of the recuperated cycle.

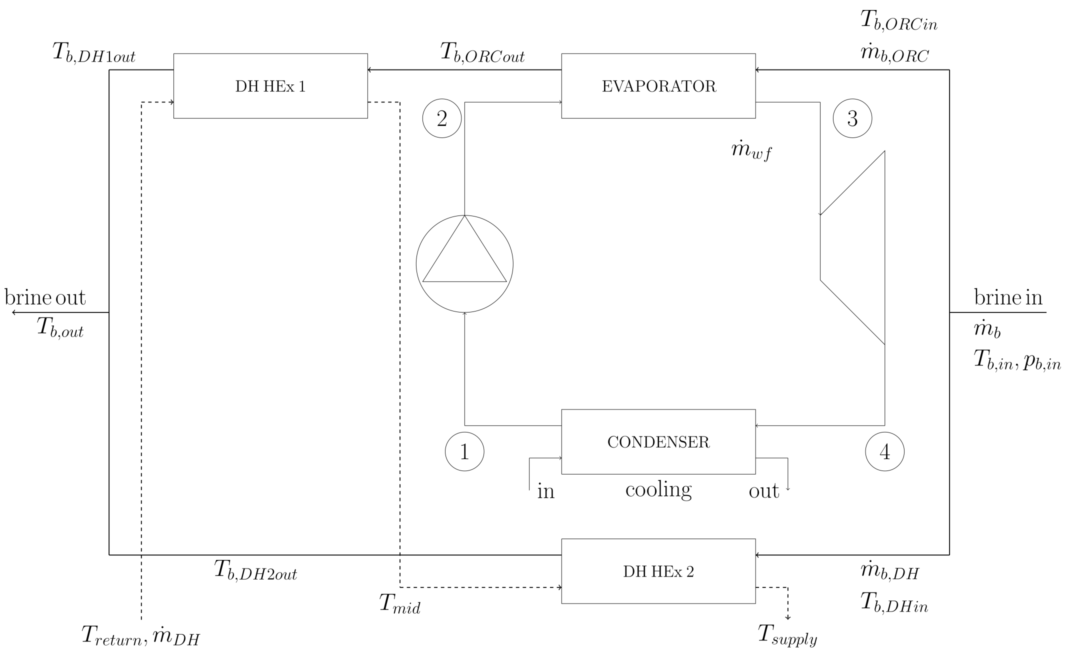


Figure 1: Preheat-parallel configuration, with indication of the nomenclature.

190 *2.2. Models*

All heat exchangers are modeled in an analogous way. The evaporator is given as an example:

$$\dot{Q}_{ORC} = \dot{m}_{b,ORC}\left(h_{b,ORCin} - h_{b,ORCout}\right) = \dot{m}_{wf}\left(h_3 - h_2\right) \tag{1}$$

The conventional symbols are used and are additionally explained in the nomenclature.

The pump and turbine mechanical powers are also calculated analogously. The turbine power is given as an example:

$$\dot{W}_t = \dot{m}_{wf}\left(h_3 - h_4\right) \text{ using } \eta_t = \frac{h_3 - h_4}{h_3 - h_{4s}} \tag{2}$$

with η_t the turbine isentropic efficiency.

The mixing of two streams is modeled as:

$$\dot{m}_b = \dot{m}_{b,ORC} + \dot{m}_{b,DH} \tag{3}$$

$$\dot{m}_b h_{b,out} = \dot{m}_{b,ORC} h_{b,DH1out} + \dot{m}_{b,DH} h_{b,DH2out} \tag{4}$$

2.3. Optimization objective

The objective is to maximize the electrical power output of the ORC while satisfying the heat demand of the DH system. No back-up boilers or thermal energy storage systems are considered. The net electrical power output $\dot{W}_{net}$ is:

$$\dot{W}_{net} = \dot{W}_t \, \eta_g - \frac{\dot{W}_p}{\eta_m} - \dot{W}_{wells} \tag{5}$$

with η_g the generator efficiency, η_m the motor efficiency and $\dot{W}_{wells} = 600kW$ the pumping power of the well pumps.

Next to the net electrical power output, different CHP configurations will be compared based on the exergetic plant efficiency η_{ex}:

$$\eta_{ex} = \frac{\dot{W}_{net} + \dot{E}x_{DH}}{\dot{E}x_{b,in}} \tag{6}$$

CHP plants have two useful outputs, the net electrical power generation $\dot{W}_{net}$ and the thermal power (i.e., heat) delivery to the DH system. The exergy flow $\dot{E}x_{DH}$ takes into account the temperatures of the DH system. The available flow exergy in the geothermal source is $\dot{E}x_{b,in}$. For example, the brine flow exergy is defined as $\dot{E}x_{b,in} = \dot{m}_b ex_{b,in}$ with ex the specific flow exergy which is generally calculated by:

$$ex = h - h_{ref} - T_{ref}\,(s - s_{ref}) \tag{7}$$

The flow exergy to the DH system is calculated as follows:

$$\dot{E}x_{DH} = \dot{E}x_{DH1} + \dot{E}x_{DH2} \tag{8}$$

$$= \dot{m}_{DH}\,(ex_{supply} - ex_{return}) \tag{9}$$

2.4. Assumptions and implementation

The following assumptions hold:

- Kinetic and potential energy differences are neglected;
- No pressure drops in the heat exchangers or piping;
- Pinch point temperature difference is $\Delta T_{pinch} = 5°C$ [4, 15];
- The working fluid in state 1 is saturated liquid at $25°C$;

- Isentropic pump and turbine efficiencies: $\eta_p = 80\%$ & $\eta_t = 85\%$ [26, 27];
- Motor and generator efficiencies: $\eta_m = 98\%$ & $\eta_g = 98\%$ [6];
- Reference state: $T_{ref} = 15°C$ & $p_{ref} = 1bar(a)$;
- Cooling inlet state: $T_c = 15°C$ & $p_c = 2bar(a)$;
- Superheating: $\Delta T_{sup} = 0.01°C$ for numerical stability.

R236ea is considered as the working fluid. No superheating is needed for this isentropic working fluid as it would decrease the plant performance [28].

The models are implemented in Python [29] and the optimal operating conditions are found using the CasADi [30] optimization framework together with the IpOpt [31] non-linear solver. Fluid properties are called from the RefProp 8.0 database [32].

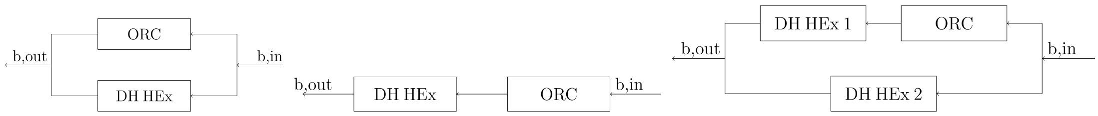
The validation of the ORC model and of the series and parallel CHP configurations has been shown in previous work [5].

3. Optimization results

The parallel, series and "Preheat-parallel" CHP configurations have been studied for the connection to a DH system with supply and return temperatures in the range of $T_{supply} = 40 - 110°C$ and $T_{return} = 30 - 70°C$, and for multiple values of the heat demand $\dot{Q}_{DH} = 3$, 6 and $9MW$. Figure 2 shows a schematic outline of the parallel, series and "Preheat-parallel" configurations. b, in and b, out represent the brine inlet and outlet, respectively, corresponding to the nomenclature of Figure 1.

Previous studies [5, 26] have shown that the implementation of a recuperator is only useful in case of a constrained ORC outlet temperature $T_{b,ORCout}$[4]. In the parallel configuration, the ORC performance does not depend on the temperature levels of the DH system such that the basic ORC is always used. However, depending on the temperature levels of the DH system, the basic or

[4]The brine has a very low salt content such that scaling risks are very low, so there was no constraint on the brine injection temperature considered. Besides, the geothermal brine is modeled as pure water.



(a) Parallel (b) Series (c) Preheat-parallel

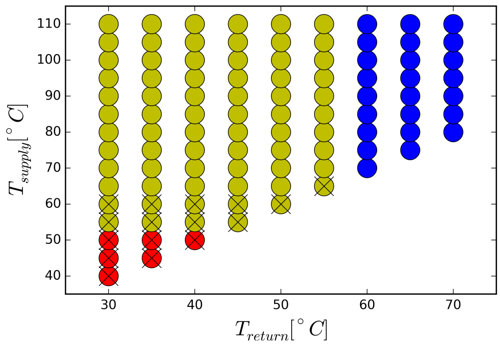
Figure 2: Schematic outline of the parallel, series and "Preheat-parallel" CHP configurations.

recuperated ORC is used in the series and "Preheat-parallel" configurations. This will be explained more in detail in the next sections.

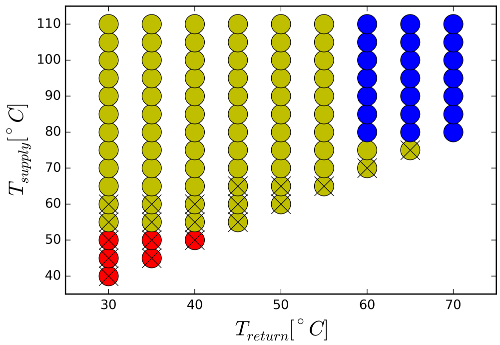
3.1. Optimal CHP configuration

The goal is to identify the most appropriate CHP configuration for the connection to a DH system with imposed T_{supply}, T_{return} and $\dot{Q}_{DH}$. Figure 3 shows the results. For each combination of the supply and return temperatures of the DH system, the optimal CHP configuration is indicated by the dot color. Red, yellow and blue indicate the "Preheat-parallel" configuration with a basic ORC, the "Preheat-parallel" configuration with a recuperated ORC and the parallel configuration, respectively. The series configuration is a special case of the "Preheat-parallel" configuration, namely the case when no brine flow rate is passing the parallel branch and the entire flow rate passes the ORC. If the series connection is the most optimal, this is indicated by a black cross on the red or yellow dot. As a remark, the parallel configuration can not be seen as a special case of the "Preheat-parallel" configuration because of the imposed pinch point temperature difference. Using the set-up of the "Preheat-parallel" configuration (see Figure 1), the ORC outlet temperature is always constrained by $T_{return} + \Delta T_{pinch}$, whereas in reality, the ORC performance in the parallel configuration does not depend on the DH temperatures.

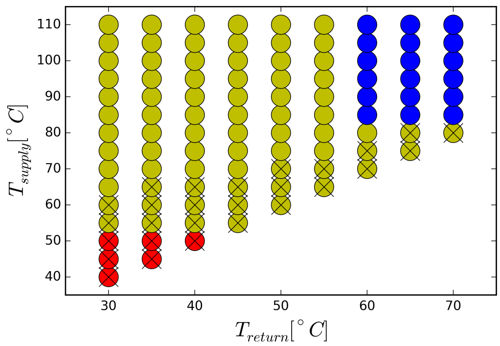
From Figure 3, it follows that for low DH temperatures, the series configurations with basic ORC (red dot with black cross) is the most appropriate. The optimal ORC outlet temperature $T^{opt}_{b,ORCout}$ for maximal electrical power production depends on the ORC inlet temperature and the working fluid. From the model results we find that for the investigated conditions, $T_{b,ORCin} = 130°C$ and R236ea, the optimal ORC outlet temperature for the basic ORC is $T^{opt}_{b,ORCout} = 57.15°C$. So for $T_{b,ORCout} = T_{supply} + \Delta T_{pinch} \leq 57.15°C$ or $T_{supply} \leq 52.15°C$, the series configuration with basic ORC is the most appropriate. For higher values of T_{supply}, the series configuration with recuperated



(a) $\dot{Q}_{DH} = 3MW$



(b) $\dot{Q}_{DH} = 6MW$



(c) $\dot{Q}_{DH} = 9MW$

Figure 3: Optimal CHP configuration as a function of T_{supply} and T_{return}. Color code: red: "Preheat-parallel" with basic ORC, yellow: "Preheat-parallel" with recuperated ORC, black cross: series connection (being a limit case of the "Preheat-parallel" scheme), blue: parallel.

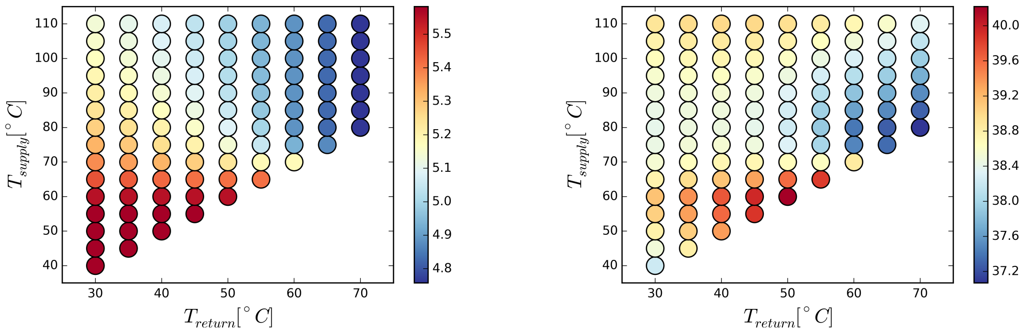
ORC (yellow dot with black cross) is more appropriate because of the stringent constraint on $T_{b,ORCout}$. The model results show that for the recuperated ORC $T^{opt}_{b,ORCout} = 62.18°C$, which is higher than for the basic ORC due to internal heat recuperation in the recuperator. The "ORC waste heat" of the recuperated cycle can be used for $T_{supply} \leq 57.18°C$ without loss in electrical power output. For higher values of T_{supply}, the series configuration with recuperated ORC might still be the most appropriate, but less electrical power is generated by the ORC due to an increase of $T_{b,ORCout}$ over its optimal value $T^{opt}_{b,ORCout}$.

For high heat demands and high values of T_{return}, it may even be better to use a series configuration (indicated by the black cross). In case of a small temperature difference $T_{supply}-T_{return}$, a high mass flow rate is needed to transfer the same amount of heat to the DH system. Since the ORC electrical power output varies linearly with $\dot{m}_{b,ORC}$, it is better to increases the ORC outlet temperature over its optimal value, which has also a negative effect on the power generation, but the effect is less severe than lowering $\dot{m}_{b,ORC}$ too much.

Furthermore, Figure 3 shows that the "Preheat-parallel" configuration with recuperator (yellow dot) is the most appropriate configuration for a wide range of T_{supply} & T_{return}. The *preheating*-effect of the "Preheat-parallel" configuration (in DH HEx 1) is more useful for a large temperature difference $T_{supply} - T_{return}$. Especially for low values of T_{return}, a large share of the heat can be delivered by the "ORC waste heat" (in DH HEx 1), which is the main advantage of the "Preheat-parallel" configuration.

Finally, the high-temperature range is investigated. Consider first a low value of the heat demand, e.g. $\dot{Q}_{DH} = 3MW$. For very high temperature levels, the parallel configuration is the most appropriate. For high values of T_{return}, the "ORC waste heat" can not be used for preheating and all heat is delivered to the DH system in the parallel branch at a high temperature. The value for the return temperature T_{return} for which the transition of "Preheat-parallel" to parallel configuration occurs, depends on $T^{opt}_{b,ORCout}$. As we are considering the "Preheat-parallel" configuration with recuperated ORC (yellow dots), $T^{opt}_{b,ORCout} = 62.18°C$, which corresponds to $T_{return} = 57.18°C$. For $T_{return} \leq 57.18°C$, some preheating is possible without loss in electrical power output. $T_{b,ORCout}$ might be increased by some degrees without decreasing the power output too much. But at a value of $T_{return} \approx 60°C$ or $T_{b,ORCout} \approx 65°C$, the parallel configuration becomes more appropriate.

For higher heat demands, it makes sense to increase the value of $T_{b,ORCout}$ over the optimal value



(a) $\dot{W}_{net}$ [MW] (b) η_{ex} [%]

Figure 4: Net electrical power output $\dot{W}_{net}$ and exergetic plant efficiency η_{ex} as a function of T_{supply} and T_{return} for $\dot{Q}_{DH} = 6MW$.

of $62.18°C$. Since $T^{opt}_{b,ORCout}$ corresponds to the maximal electrical power output of the system, a deviation of $T_{b,ORCout}$ from $T^{opt}_{b,ORCout}$ has always a negative impact on the power output. However, by increasing $T_{b,ORCout}$, more heat can be provided to the DH system in DH HEx 1 (*preheating-effect*). This way, less mass flow rate is needed in the parallel branch (with DH HEx 2) and the mass flow rate through the ORC branch can be kept as high as possible. The increase of $T_{b,ORCout}$ over $T^{opt}_{b,ORCout}$ has a negative impact on $\dot{W}_{net}$ but a higher mass flow rate through the ORC branch has a positive impact on $\dot{W}_{net}$. The effect of the mass flow rate is the most outspoken. As a result, the "Preheat-parallel" configuration, and for small temperature differences $T_{supply} - T_{return}$ even the series configurations, become more interesting for higher heat demands of the DH system (see Figure 3c).

3.2. Optimal plant performance

Figure 4 shows the net electrical power output $\dot{W}_{net}$ and exergetic plant efficiency η_{ex} as a function of T_{supply} and T_{return}. The results are shown for $\dot{Q}_{DH} = 6MW$ and correspond to the optimal configurations of Figure 3b.

Figure 4a shows the net power output. From before we know that the optimal ORC outlet temperatures are $T^{opt}_{b,ORCout} = 57.15°C$ and $T^{opt}_{b,ORCout} = 62.18°C$ for the basic and the recuperated ORC, respectively. From Figure 3b follows that the series configuration with basic ORC is the most optimal up to $T_{b,ORCout} = 57.15°C$ or $T_{supply} = 52.15°C$. For $T_{supply} > 52.15°C$, the series configuration with recuperated ORC becomes optimal. Up to $T_{b,ORCout} = 62.18°C$ or $T_{supply} = 57.18°C$, the maximal electrical power output of $\dot{W}_{net} = 5.58MW$ is produced. This equals the power output of a pure electrical power plant and the "ORC waste heat" suffices to satisfy the heat demand $\dot{Q}_{DH}$. For supply temperatures slightly higher than $57.18°C$, the series configuration with recuperated ORC is still the most appropriate but the electrical power output is lower due to an increase of $T_{b,ORCout}$ over $T^{opt}_{b,ORCout}$.

For higher values of T_{supply}, the "Preheat-parallel" configuration is the optimal configuration. Less brine flow rate is passing through the ORC branch and the net electrical power output decreases. A higher value of T_{return} decreases the preheating potential in DH HEx 1, a higher value of T_{supply} either increases the heat which has to be delivered in the parallel branch at a high temperature (in DH HEx 2) or increases the value of $T_{b,ORCout}$. So, increasing the DH temperatures results in a lower electrical power output.

For high DH temperatures, the parallel configuration is optimal. However, the brine mass flow rate which flows through the ORC branch is lower such that even less electrical power is produced.

Figure 4b shows the exergetic plant efficiency. The maximal exergetic plant efficiency is reached for $T_{supply} = 60°C$ & $T_{return} = 50°C$. For $T_{supply} = 60°C$, the electrical power production is $\dot{W}_{net} = 5.55MW$, which is only 0.5% lower than the net power output of a pure electrical power plant. Besides, the temperature of the heat which is delivered to the DH system is relatively high and hence the flow exergy $\dot{Ex}_{DH}$ has also a relatively high value. These two effects result in an exergetic plant efficiency of $\eta_{ex} = 40.22\%$.

First, the influence of T_{supply} is studied. For $T_{supply} \leq 60°C$, the series configurations are the most appropriate (see Figure 3b). The power output is almost constant ($\dot{W}_{net} = 5.58MW$ for $T_{supply} \leq 57.18°C$ down to $\dot{W}_{net} = 5.55MW$ for $T_{supply} = 60°C$), so for lower DH temperatures $\dot{Ex}_{DH}$ decreases and also η_{ex} decreases. In case the "Preheat-parallel" configuration is optimal, there is a trade-off between the influence of $\dot{W}_{net}$ on the one hand, and the temperatures of heat delivery on the other hand. Starting from a low value of T_{supply} and increasing its value, $\dot{W}_{net}$ decreases as was shown on Figure 4a. But the value of $\dot{Ex}_{DH}$ increases with the DH temperatures. On Figure 4b we see that for an increase of T_{supply}, first the $\dot{W}_{net}$ effect dominates which decreases η_{ex} and for high values of T_{supply}, the $\dot{Ex}_{DH}$ effect starts to dominate and η_{ex} increases again.

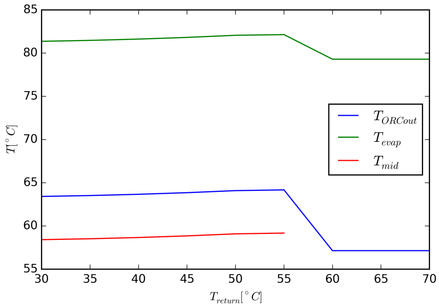
In addition, the effect of T_{return} has been investigated and is now discussed. For low values of T_{supply}, increasing T_{return} has a positive effect on η_{ex} because $\dot{W}_{net}$ stays approximately constant and the mean temperature of the heat delivery increases. For higher values of T_{supply}, $\dot{W}_{net}$ decreases very fast with T_{return}. $\dot{W}_{net}$ is the dominating effect so that also η_{ex} decreases.

3.3. Influence of DH temperatures on plant performance

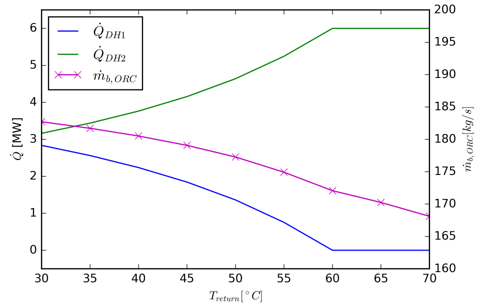
The influence of the DH temperatures on the system operating conditions is now studied more in detail. The variables of interest are the brine mass flow rate through the ORC branch $\dot{m}_{b,ORC}$, the ORC outlet temperature $T_{b,ORCout}$, the evaporator temperature T_{evap} and the temperature of the DH system after preheating T_{mid}. Also the heat delivery by the two heat exchangers (DH HEx 1 & DH HEx 2) is discussed. Figure 5 shows the results for $\dot{Q}_{DH} = 6MW$ and for three decreasing values of the supply temperature: $T_{supply} = 90,\, 70\,\&\, 50°C$.

Figures 5a to 5f correspond to a horizontal cut of Figure 3b at $T_{supply} = 90,\, 70\,\&\, 50°C$. Some general trends are that the value of T_{mid} is always lower than $T_{b,ORCout}$ by the assumed pinch point difference of $\Delta T_{pinch} = 5°C$. Also, the evaporator temperature follows the same trend. The optimal evaporator temperature depends on the ORC inlet and outlet temperatures. As the ORC inlet temperature is always equal to the brine inlet temperature, T_{evap} only depends on $T_{b,ORCout}$.

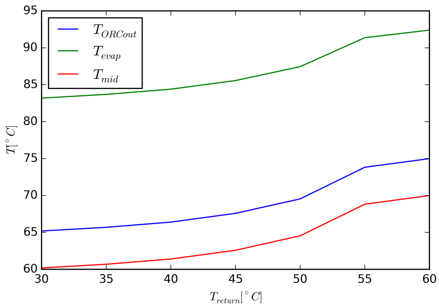
First consider $T_{supply} = 90°C$. $T_{b,ORCout}$, T_{mid} & T_{evap} increase slightly with T_{return} (Figure 5a). $T_{b,ORCout} > T^{opt}_{b,ORCout} = 62.18°C$ to exploit the preheating of the "Preheat-parallel" configuration and to keep the mass flow rate through the ORC branch $\dot{m}_{b,ORC}$, and hence $\dot{W}_{net}$, as high as possible. Furthermore, the *preheating*-effect/use of the "ORC waste heat" in DH HEx 1 decreases with T_{return} and more heat has to be delivered by DH HEx 2 in the parallel branch. As a result, $\dot{m}_{b,ORC}$ decreases (Figure 5b). For $T_{return} \geq 60°C$, the parallel configuration is the optimal configuration. Therefore T_{mid} stops and there are jumps in the trends for $T_{b,ORCout}$ & T_{evap}. From now on, $T_{b,ORCout} = T^{opt}_{b,ORCout} = 57.15°C$, the optimal value of the basic ORC, because there is no dependence on the DH temperatures for the parallel configuration. The heat is fully delivered by DH HEx 2 in the parallel branch. In order to satisfy the fixed heat demand of $\dot{Q}_{DH} = 6MW$, the mass flow rate through the parallel branch (with DH HEx 2) increases with T_{return} (since



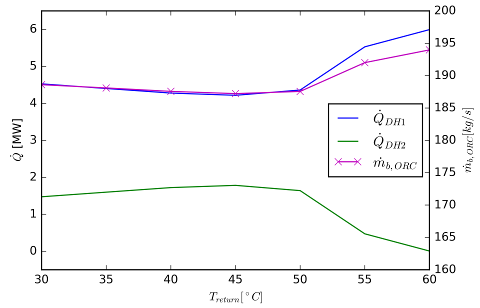
(a) $T_{supply} = 90^\circ C$



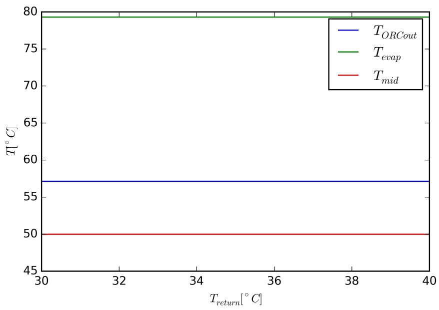
(b) $T_{supply} = 90^\circ C$



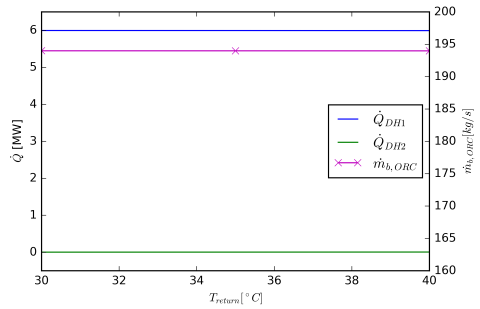
(c) $T_{supply} = 70^\circ C$



(d) $T_{supply} = 70^\circ C$



(e) $T_{supply} = 50^\circ C$



(f) $T_{supply} = 50^\circ C$

Figure 5: Influence of T_{supply} & T_{return} on the system variables: $T_{b,ORCout}$, T_{evap}, T_{mid} & $\dot{m}_{b,ORC}$ (x-mark) and on the heat delivery by DH HEx 1 & DH HEx 2 for $\dot{Q}_{DH} = 6MW$. The left-hand panels show the temperatures, the right-hand panels the heat delivered by DH HEx 1 & DH HEx 2, and the mass flow rate in the ORC branch; each time for three decreasing values of the supply temperature: $T_{supply} = 90,\ 70\,\&\,50^\circ C$.

$T_{supply} - T_{return}$ decreases with T_{return} for a fixed $T_{supply} = 90°C$). Hence, $\dot{m}_{b,ORC}$ decreases with T_{return}.

Second, consider $T_{supply} = 70°C$. As for the previous case, $T_{b,ORCout}$, T_{mid} & T_{evap} increase slightly with T_{return} (Figure 5c) to promote preheating and a high brine mass flow rate through the ORC. T_{supply} is only slightly higher than $T_{b,ORCout}$ such that only a small share of heat needs to be delivered by DH HEx 2. So, $\dot{m}_{b,ORC}$ is high and almost equal to the total brine flow rate $\dot{m}_b = 194kg/s$. For a higher T_{return}, the temperature difference $T_{supply} - T_{return}$ is smaller and slightly more flow rate is required in the parallel branch, hence $\dot{m}_{b,ORC}$ decreases slightly (Figure 5d). Correspondingly, $\dot{Q}_{DH1}$ decreases and $\dot{Q}_{DH2}$ increases slightly. However, for even higher values of T_{return}, it is better to increase the flow rate to the ORC branch (positive effect on $\dot{W}_{net}$) and increase $T_{b,ORCout}$ (negative effect on $\dot{W}_{net}$). The overall effect on $\dot{W}_{net}$ is positive. For $T_{return} = 60°C$, the temperature difference $T_{supply} - T_{return}$ is only $10°C$ and it is even more profitable to use the series configuration. All heat is delivered in DH HEx 1 and no brine flow rate passes the parallel branch. So, increasing $T_{b,ORCout}$ is favorable in case of small $T_{supply} - T_{return}$ to keep the flow rate through the ORC branch $\dot{m}_{b,ORC}$, and hence $\dot{W}_{net}$, high.

Finally, consider $T_{supply} = 50°C$. The series configuration with basic ORC is the most appropriate and the ORC operating parameters and power output are independent of T_{return}[5]. The ORC produces maximal electricity $\dot{W}_{net} = 5.58MW$ at $T_{b,ORCout} = T^{opt}_{b,ORCout} = 57.15°C$ (Figure 5e). The entire brine flow rate passes the ORC branch and the heat demand is satisfied by the "ORC waste heat" in DH HEx 1 (Figure 5f).

In general, T_{return} is kept as low as possible to reduce the losses of the DH system and a higher temperature difference $T_{supply} - T_{return}$ is desirable to reduce the pumping power [33]. Moreover, we found that low DH temperatures (both T_{return} as well as T_{supply}) result in the highest electrical power output and the highest plant efficiency.

[5]Only if the heat demand is not too high. A very high heat demand would put a more stringent constraint on the ORC outlet temperature. The pinch point location would be at the brine injection side of DH HEx 1. As a result, the power output and exergetic plant efficiency would be lower.

$\dot{Q}_{DH} [MW]$		series	series recup	parallel	"Preheat-parallel"	"Preheat-parallel" recup
3	$\dot{W}_{net}$ [MW]	4.57	4.87	5.28	5.31	5.35
	η_{ex} [%]	31.96	33.90	36.51	36.67	36.94
6	$\dot{W}_{net}$ [MW]	4.57	4.87	4.98	5.03	5.14
	η_{ex} [%]	34.67	36.61	37.27	37.61	38.31
9	$\dot{W}_{net}$ [MW]	4.57	4.87	4.67	4.82	4.97
	η_{ex} [%]	37.38	39.32	38.04	38.98	39.97

Table 1: Comparison of the series, parallel and "Preheat-parallel" CHP configurations for the connection to a state-of-the-art 75/50 DH system.

3.4. Case study: connection to a state-of-the-art 75/50 district heating network

The "Preheat-parallel" configuration is now compared with the series and parallel configuration for the connection to a 75/50 DH system, which is a state-of-the-art thermal network [4, 15]. Table 1 summarizes the results for three values of the heat demand.

First, the influence of the heat demand on each CHP configuration is discussed. The electrical power output of the series configuration is independent of the heat demand[6]. The exergetic plant efficiency increases as a result of the higher heat demand.

The electrical power output of the parallel configuration decreases with the heat demand due to a lower brine flow rate through the ORC branch. For the investigated values of T_{supply} & T_{return}, the increase in heat flow exergy is compensating for the loss in electrical power output and η_{ex} increases.

For the "Preheat-parallel" configurations, the electrical power output decreases with the heat demand. However, the effect is less in comparison to the parallel configuration due to the *preheating*-effect. Typically, the ORC outlet temperature is increased (negative effect on $\dot{W}_{net}$) such that the brine flow rate through the ORC branch can be kept relatively high (positive effect on $\dot{W}_{net}$). As for the parallel configuration, the increase in exergy flow is the dominating effect on the plant efficiency, such that η_{ex} increases.

[6]Only if the heat demand is not too high.

Second, the different CHP configurations are compared for the same value of the heat demand for the connection to a 75/50 DH system (horizontal comparison in Table 1). The series configuration with basic ORC is the worst configuration. The ORC outlet temperature has to be increased too much over its optimal value which results in a very low electrical power output $\dot{W}_{net}$. Correspondingly, also the exergetic plant efficiency is low. The series configuration with a recuperated ORC performs better. Since the optimal ORC outlet temperature $T^{opt}_{b,ORCout}$ is a bit higher due to the internal heat recuperation, the increase of the ORC outlet temperature over its optimal value is smaller and the electrical power output is higher.

The parallel configuration performs better than the series configuration for low heat demands. A large share of the brine flow rate is sent to the ORC branch and $T_{b,ORCout} = T^{opt}_{b,ORCout}$. This leads to a higher electrical power output and a higher value of the exergetic plant efficiency. However, for high heat demands, the parallel configuration performs worse than the series configuration with recuperated ORC. A too large share of the brine flow rate is going to the parallel branch to satisfy the heat demand and less power is produced due to a lower $\dot{m}_{b,ORC}$. The transition occurs at a heat demand of $\dot{Q}_{DH} = 7MW$.

The "Preheat-parallel" configuration performs better than the series and parallel configurations and it combines the good aspects of both. The *preheating*-effect/"ORC waste heat" is used to heat the DH fluid up to an intermediate temperature level. Only a small share of the heat is delivered in the parallel branch. Typically, $T_{b,ORCout}$ is increased over its optimal value but the brine flow rate to the ORC branch is kept as high as possible. The overall effect on $\dot{W}_{net}$ is positive. The "Preheat-parallel" configuration using a recuperated ORC has the best performance. Analogue to the series configurations, $T^{opt}_{b,ORCout}$ of the recuperated ORC is higher than for the basic cycle, such that the effect of increasing the ORC outlet temperature over its optimal value is smaller which results in a larger electrical power output. This also leads to a smaller influence of the heat demand on the electrical power output.

4. Conclusions

In this work, we have presented the novel "Preheat-parallel" CHP configuration which delivers heat to a district heating (DH) system and is fueled by low-temperature geothermal energy. The

”Preheat-parallel” configuration has been discussed and its performance has been compared with the convenient series and parallel CHP configurations. The following conclusions are made:

1. regarding the ORC performance:

    - There exists an optimal value of the ORC outlet temperature $T_{b,ORCout}^{opt}$ for which the electrical power output is maximal, depending on the ORC inlet temperature and the working fluid.

    - The value of $T_{b,ORCout}^{opt}$ is higher in case of a recuperated ORC than for the basic ORC due to internal heat recovery. As a result, a constraint on $T_{b,ORCout}$ has less effect on the electrical power output of the recuperated ORC in comparison to the basic ORC and the recuperated cycle is preferred in case of a constrained $T_{b,ORCout}$.

    - There are two main parameters influencing the power output of the ORC. First, the electrical power production depends linearly on the brine flow rate to the ORC. And second, an ORC outlet temperature $T_{b,ORCout}$ different from $T_{b,ORCout}^{opt}$ decreases the electrical power output.

2. regarding the optimal CHP configurations:

    - Low values of the DH temperatures (both T_{supply} and T_{return}) lead to the highest electrical power output and the highest exergetic plant efficiency.

    - The optimal CHP configuration depends on the DH temperatures:

        - For low values of T_{supply}, the series configuration has the best performance, independent of the value of T_{return}. This configuration has the highest exergetic plant efficiency.

        - The ”Preheat-parallel” configuration is the most appropriate for low values of T_{return} and a large temperature difference $T_{supply} - T_{return}$, exploiting the preheating potential of the ”Preheat-parallel” configuration.

        - The parallel configuration is the most suitable for high DH temperatures. This configuration has the lowest exergetic plant efficiency.

3. regarding the ”Preheat-parallel” configuration:

- The "Preheat-parallel" configuration is the most optimal configuration for a wide range of values for T_{supply} and T_{return}.
- If the "Preheat-parallel" configuration is optimal, the ORC outlet temperature is always constrained by the DH temperatures such that the recuperated cycle is preferred over the basic ORC.
- Increasing the ORC outlet temperature (and thereby enhancing the preheating-effect) is of interest in case of a high value of T_{return}, especially for low temperature differences $T_{supply} - T_{return}$.
- The higher the heat demand, the more useful the preheating-effect. In case of high heat demands and high values of T_{return}, the series or "Preheat-parallel" configurations might perform even better than the parallel configuration.
- From the case study follows that the "Preheat-parallel" configuration is the most appropriate for the connection to a state-of-the-art 75/50 DH system. For a heat demand of $\dot{Q}_{DH} = 6MW$, the net electrical power output is $\dot{W}_{net} = 5.14MW$, which is 3.11% and 5.25% higher than for the parallel and series configurations, respectively. The corresponding exergetic plant efficiency is $\eta_{ex} = 38.31\%$.

For future work, we plan to implement thermo-economic models for the proposed CHP systems. Based on these thermo-economic (optimization) model results, we will be able to compare the economics of the different CHP configurations.

Acknowledgments

This project receives the support of the European Union, the European Regional Development Fund ERDF, Flanders Innovation & Entrepreneurship and the Province of Limburg.

Nomenclature

Symbols

symbol	description
%-pts	percentage points
$\dot{Ex}$ [MW]	flow exergy
ex [kJ/kg]	specific flow exergy
h [kJ/kg]	specific enthalpy
$\dot{m}$ [kg/s]	mass flow rate
$\dot{Q}$ [MW]	heat
s [kJ/kgK]	specific entropy
T [$^{\circ}C$]	temperature
$\dot{W}$ [MW]	electrical power
η [%]	efficiency

Subscripts & superscripts

symbol	description
1	wf state at pump inlet
2	wf state at pump outlet
3	wf state at turbine inlet
4	wf state at turbine outlet
b	brine
c	cooling water
DH	District Heating system
$evap$	evaporator
ex	exergetic
g	generator
in	inlet
m	motor
mid	between DH HEx 1 & DH HEx 2
net	net
opt	optimal (corresponding to maximal $\dot{W}_{net}$)
ORC	Organic Rankine Cycle
out	outlet
p	pump
$pinch$	pinch point
$recup$	recuperator
ref	reference state
$return$	return state DH system
s	isentropic
sup	superheating
$supply$	supply state DH system
t	turbine
$wells$	geothermal wells
wf	working fluid

References

[1] IEA, Technology Roadmap - Geothermal Heat and Power, Technical Report, OECD, Paris, 2011. URL: https://www.iea.org/newsroomandevents/pressreleases/2011/june/how-to-achieve-at-least-a-tenfold-increase-in-supply-of-geothermal-power-and-hea.html.

[2] R. DiPippo, Geothermal Power Plants: Principles , Applications , Case Studies and Environmental Impact, third ed., 2005.

[3] MIT, The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century, November, Cambridge, UK, 2006. URL: http://www.eere.energy.gov/geothermal/pdfs/structure_outcome.pdf.

[4] F. Heberle, D. Brüggemann, Exergy based fluid selection for a geothermal Organic Rankine Cycle for combined heat and power generation, Applied Thermal Engineering 30 (2010) 1326–1332.

[5] S. Van Erdeweghe, J. Van Bael, B. Laenen, W. D'haeseleer, Comparison of series/parallel configuration for a low-T geothermal CHP plant, coupled to thermal networks, Working Paper, submitted to Renewable Energy (2016).

[6] M. Astolfi, L. Xodo, M. C. Romano, E. Macchi, Technical and economical analysis of a solar-geothermal hybrid plant based on an Organic Rankine Cycle, Geothermics 40 (2011) 58–68.

[7] D. Tempesti, D. Fiaschi, Thermo-economic assessment of a micro CHP system fuelled by geothermal and solar energy, Energy 58 (2013) 45–51.

[8] C. Zhou, E. Doroodchi, B. Moghtaderi, An in-depth assessment of hybrid solargeothermal power generation, Energy Conversion and Management 74 (2013) 88–101.

[9] C. Zhou, Hybridisation of solar and geothermal energy in both subcritical and supercritical Organic Rankine Cycles, Energy Conversion and Management 81 (2014) 72–82.

[10] J. M. Cardemil, F. Cortés, A. Díaz, R. Escobar, Thermodynamic evaluation of solar-geothermal hybrid power plants in northern Chile, Energy Conversion and Management 123 (2016) 348–361.

[11] T. Li, J. Zhu, W. Zhang, Comparative analysis of series and parallel geothermal systems combined power, heat and oil recovery in oilfield, Applied Thermal Engineering 50 (2013) 1132–1141.

[12] C. Rubio-Maya, V. M. Ambríz Díaz, E. Pastor Martínez, J. M. Belman-Flores, Cascade utilization of low and medium enthalpy geothermal resources - A review, Renewable and Sustainable Energy Reviews 52 (2015) 689–716.

[13] D. Fiaschi, A. Lifshitz, G. Manfrida, D. Tempesti, An innovative ORC power plant layout for heat and power generation from medium- to low-temperature geothermal resources, Energy Conversion and Management 88 (2014) 883–893.

[14] T. Guo, H. Wang, S. Zhang, Fluids and parameters optimization for a novel cogeneration system driven by low-temperature geothermal sources, Energy 36 (2011) 2639–2649.

[15] M. Habka, S. Ajib, Investigation of novel, hybrid, geothermal-energized cogeneration plants based on organic Rankine cycle, Energy 70 (2014) 212–222.

[16] V. Zare, A comparative thermodynamic analysis of two tri-generation systems utilizing low-grade geothermal energy, Energy Conversion and Management 118 (2016) 264–274.

[17] M. Akbari Kordlar, S. Mahmoudi, Exergeoconomic analysis and optimization of a novel cogeneration system producing power and refrigeration, Energy Conversion and Management 134 (2017) 208–220.

[18] F. A. Boyaghchi, H. Safari, Parametric study and multi-criteria optimization of total exergetic and cost rates improvement potentials of a new geothermal based quadruple energy system, Energy Conversion and Management 137 (2017) 130–141.

[19] E. Akrami, A. Chitsaz, H. Nami, S. Mahmoudi, Energetic and exergoeconomic assessment of a multi-generation energy system based on indirect use of geothermal energy, Energy (2017).

[20] E. Bellos, C. Tzivanidis, K. A. Antonopoulos, Parametric investigation and optimization of an innovative trigeneration system, Energy Conversion and Management 127 (2016) 515–525.

[21] C. Wieland, D. Meinel, S. Eyerer, H. Spliethoff, Innovative CHP concept for ORC and its benefit compared to conventional concepts, Applied Energy 183 (2016) 478–490.

[22] F. Calise, M. D. D'Accadia, A. Macaluso, A. Piacentino, L. Vanoli, Exergetic and exergoeconomic analysis of a novel hybrid solargeothermal polygeneration system producing energy and water, Energy Conversion and Management 115 (2016) 200–220.

[23] M. Wang, J. Wang, P. Zhao, Y. Dai, Multi-objective optimization of a combined cooling, heating and power system driven by solar energy, Energy Conversion and Management 89 (2015) 289–297.

[24] E. Martelli, F. Capra, S. Consonni, Numerical optimization of Combined Heat and Power Organic Rankine Cycles Part A: Design optimization, Energy 90 (2015) 310–328.

[25] F. Capra, E. Martelli, Numerical optimization of combined heat and power Organic Rankine Cycles Part B: Simultaneous design & part-load optimization, Energy 90 (2015) 329–343.

[26] D. Walraven, B. Laenen, W. D'haeseleer, Comparison of thermodynamic cycles for power production from low-temperature geothermal heat sources, Energy Conversion and Management 66 (2013) 220–233.

[27] Y.-R. Li, J.-N. Wang, M.-T. Du, S.-Y. Wu, C. Liu, J.-L. Xu, Effect of pinch point temperature difference on cost-effective performance of organic Rankine cycle, International Journal of Energy Research 31 (2013).

[28] H. Chen, D. Y. Goswami, E. K. Stefanakos, A review of thermodynamic cycles and working fluids for the conversion of low-grade heat, Renewable and Sustainable Energy Reviews 14 (2010) 3059–3067.

[29] G. van Rossum, Python Tutorial, Technical Report CS-R9526, Technical Report, Centrum voor Wiskunde en Informatica (CWI), Amsterdam, 1995. URL: `http://www.python.org`.

[30] J. Andersson, A General-Purpose Software Framework for Dynamic Optimization, Phd, Arenberg Doctoral School, KU Leuven, 2013.

[31] A. Wächter, L. T. Biegler, On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming, Mathematical Programming 106 (2006) 25–57.

[32] E. Lemmon, M. Huber, M. McLinden, REFPROP - Reference Fluid Thermodynamic and Transport Properties. NIST Standard Reference Database 23, 2007.

[33] H. Gadd, S. Werner, Achieving low return temperatures from district heating substations, Applied Energy 136 (2014) 59–67.